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Electron Plasma for Antiproton Cooling in the ATHENA Experiment

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Abstract. The first phase of the ATHENA (AnTiHydrogEN Apparatus) experiment is devoted to the study of cold antihydrogen production.

The apparatus includes an antiproton capture trap designed to trap and to cool antiprotons coming from the CERN Antiproton Decelerator (AD). The antiproton cooling is achieved by means of the collisional interaction with a cold cloud of trapped electrons. The electron plasma is loaded in the trap before the antiproton capture by means of a small-size heated filament and cooled to sub-eV temperatures by cyclotron radiation.

We report some measurements devoted to the characterization of the electron plasma. The ATHENA apparatus design does not allow the use of complex diagnostic; therefore the plasma properties are obtained using electrostatic wall probes, radio-frequency diagnostic, and dumping the electrons onto a charge collector. A simple experimental method to obtain an estimate of the electron plasma radius is discussed.

INTRODUCTION

The aim of the ATHENA experiment [1, 2] is the cold antihydrogen production for high resolution laser spectroscopy studies. The first phase of the experiment is focused on the production of low temperature antihydrogen atoms from the interaction of severals thousands antiprotons with a dense positron plasma. The two antihydrogen components are produced and accumulated in two different electromagnetic traps and then they are transferred in a nested-well plasma multi-ring trap.

The positron plasma is produced in a modified Penning-Malmberg trap based on the design described in Refs. 3 and 4 (see also Ref. 5).

The antiprotons are delivered by the Antiproton Decelerator (AD) [6] at CERN with a kinetic energy around 5 MeV. The AD antiprotons bunch pass through some degrader foils and up to $1.6 \cdot 10^4$ antiprotons are routinely caught in a high voltage trap. The trapped antiprotons are then cooled by the interaction with a cold dense electron plasma. Once antiprotons are cooled, they are transferred into the recombination trap.

In this work we will focus our attention on the electron plasma used to slow down the antiproton bunch. In the following, we present the structure of the antiproton catching trap and the electron plasma diagnostic system. We also report and discuss our experimental investigations on electron plasma properties.

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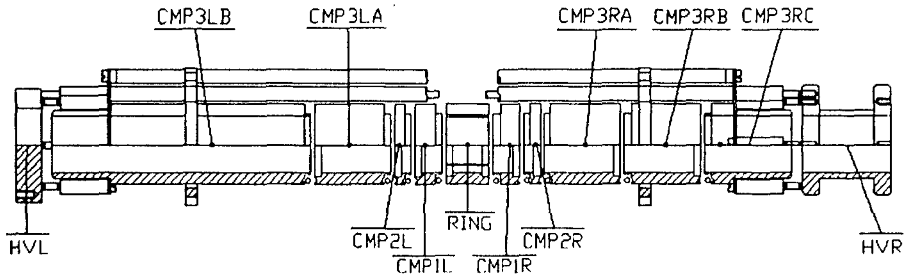

FIGURE 1. Configuration of the antiproton catching trap electrodes

ANTIPROTONS CATCHING TRAP

The antiproton catching trap is composed by 12 cylindrical electrodes (Fig. 1). The internal diameter of the electrodes is 2.5 cm while the electrodes lengths vary from 0.5 cm to 13 cm. The trap is mounted in a cryogenic ultra-high vacuum system placed in a magnetic field of 3 T.

The two external electrodes (HVR and HVL) are used to trap the antiprotons beam coming from the AD. Some foils acting as energy degraders are mounted in front of the HVL electrode and they are traversed by the antiproton beam. Among these foils there is a silicon sensor (67 μm thick) used as beam counter and a 80 μm aluminum foil closing the external side of the entrance electrode (HVL).

Before the antiprotons arrival, the far away electrode (HVR) is polarized applying up to -10 kV. After a suitable delay (few hundreds of ns) from the time when the antiprotons hit the silicon detector, the HVL voltage is rapidly (in a few tenths on ns) switched on and the particles exiting from the degrader and lying in tail of the energy distribution are captured into the trap.

The central section, composed by 10 electrodes, is used to confine the electron plasma and the cold antiprotons. The electrodes have different lengths and can be separately polarized in order to have a good flexibility in the external electrostatic field configuration. The applied potentials can be chosen in order to shape the trap region with harmonic or flat electrostatic field. The central electrode (RING) is sectored in 4 azimuthal parts to detect and drive diocotron modes.

DIAGNOSTIC SYSTEMS

Two different kind of diagnostic are implemented [7]: a destructive diagnostic based on the dumping of the electrons on the degrader foil connected with HVL electrode, and a non-destructive diagnostic of the plasma collective modes.

The destructive diagnostic consists in dumping the electrons on the degrader and measuring the collected charge by means of an high-impedance low-noise amplifier. The measurement of the total number of the electrons extracted varying the confining

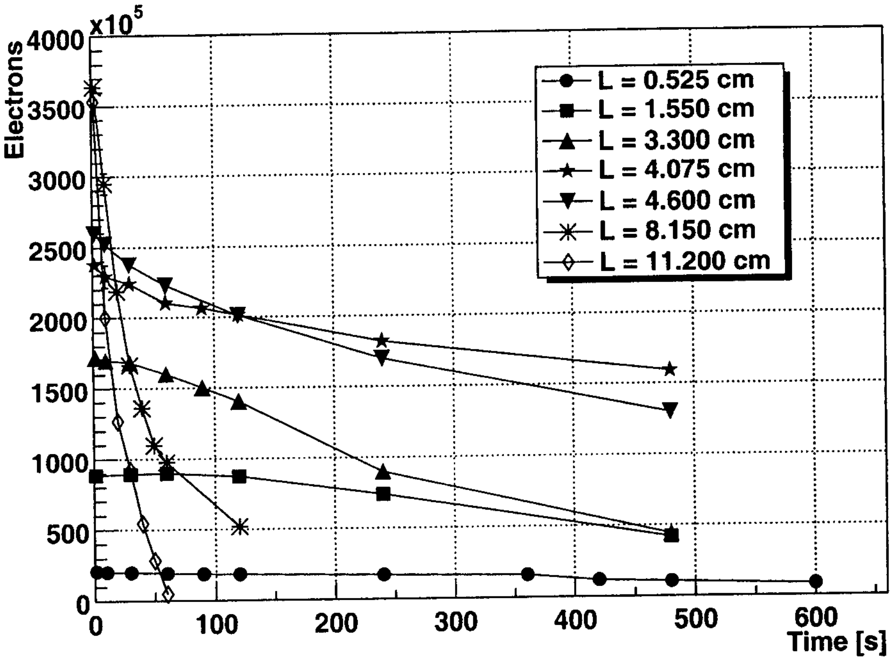

FIGURE 2. Example of the dependence of the number of loaded electrons on the confining time. The potential applied to the two confining electrodes is -35 V.

potential gives different information on the plasma. It can be used to measure the longitudinal plasma temperature [8] or, assuming a plausible temperature value, it is useful to have an indication of the radial extension of the plasma.

A fast rough estimate of the plasma radius can be obtain by the following procedure. Assuming a zero-temperature model, the electrons cloud shape is approximated by an infinite plasma column of radius R_p and constant line density $n_0 = N_i/L_T$, where L_T is the trap length. On the axis of the trap, the space charge potential $\Phi(N_i, R_p, L_T)$ is less than the external applied potential V_T and this condition assures the confinement of the plasma. If the confining potential is lowered by a suitable value ΔV, a small amount of particles leaves the trap on the axis, reducing the space charge potential until the confining condition is again satisfied. The number of escaping electrons N_e can be thought as the number of extracted particles necessary to leave an hollow cylinder charge distribution having, external radius R_p, internal radius $R_h = R_p(N_e/N_i)^{1/2}$, and a space charge potential on the trap axis $\Psi(N_i, N_e, R_p, L_T)$ equal to $V_T - \Delta V$. The measure of the total initial electrons number, and the detection of number of escaping particles as function of ΔV, combined with the analytic expression of $\Psi(N_i, N_e, R_p, L_T)$, permit to easily obtain the radius R_p and line density n_0 of the plasma.

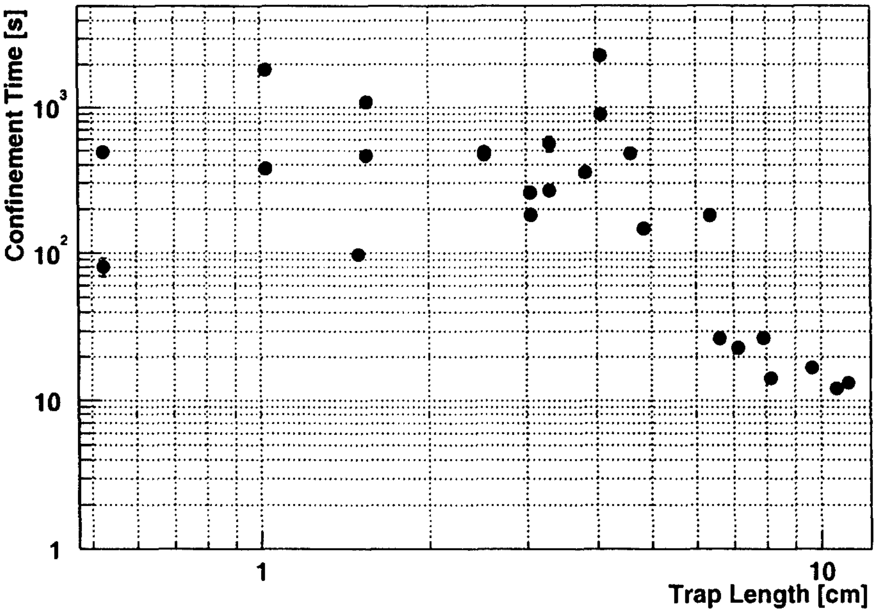

FIGURE 3. Dependence of confinement time on trap length. The confinement time is defined like the required time for one-half of the injected electrons to be lost.

The non-destructive diagnostic is based on the measure of the induced signals on electrodes due to electrons and/or antiprotons collective modes.

One of the collective modes monitored is the m=1 diocotron mode of the electron plasma. This diagnostic uses the sectors of the RING electrode. The wave is excite by applying a suitable pulse to two opposite sectors, the induced signals on the other two sectors gives the information on the frequency and the amplitude of the resulting mode. After the detection, the mode is damped by negative feedback [9]: the signal received on one wall sector is amplified, phase shifted and then applied to a second sector making the m=1 mode to damp.

When the confining electrostatic field is harmonic, is possible to extract the total number of both the electrons and the antiprotons by detecting the center mass oscillation. In an harmonic trap, the particles motion along the axis is characterized by a fixed frequency ω_z, dependent on external applied fields. A center of mass oscillation can be excited by applying on one trap electrode a drive potential having frequency close to ω_z. The resulting collective oscillation is detected by a resonant circuit connected to another electrode. Two different resonant circuits, characterized by two different resonance frequencies ($\sim$ 14 MHz and $\sim$ 1.4 MHz), are used for electrons and antiprotons. The amplitude of the induced voltage signal is proportional to the number of stored particles. An independent measure of the total number of particles is also given by the frequency shift between the collective mode and the single particle oscillation.

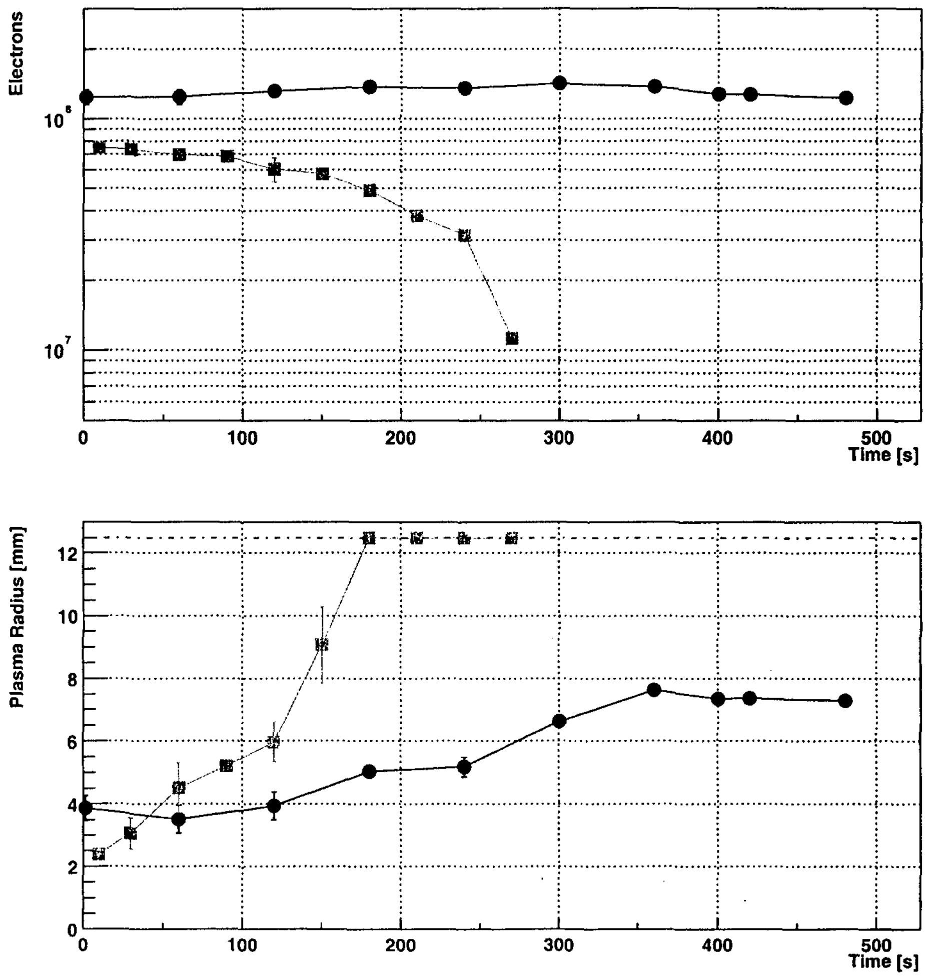

FIGURE 4. Time evolution of the total electron number and of the plasma radius for two different initial conditions.

ELECTRON PLASMA LOADING AND CONFINEMENT

The electrons are loaded in the trap using a small-size tungsten heated filament. The electron source is located about 2 m away from the antiproton trap in a low-magnetic field zone (B $\simeq$ 0.01 T). To reach the antiproton trap the electron beam passes through several grounded cylindrical electrodes composing the nested-well multi-ring trap that will be used for the recombination studies [1, 2]. The typical source emitted current is about 200 μA while the electron current that reaches the aluminum foil is less than

20 μA. The loading procedure consists in preparing a potential well of variable depth (up to 50 V) and length and leaving the filament switched on for few seconds. Plasmas with different total number of electrons (up to 10^9) and radial extension (from few millimeter to the electrodes radius) can be loaded changing the intensity of the primary beam or the shape of the electrodes potentials (Figs. 2,3 and 4).

The plasma confinement time is short respect to the expected time due to the interaction with the residual gas (the typical working pressure is less than 10^{-12} mbar). As it has been observed in similar apparatus, the loss of the plasma is due to a radial expansion connected to system asymmetries. The measured dependence of the confinement time on the plasma length is shown in Figs. 2 and 3. The lifetime of the plasma does not follow a simple length scaling, different trap regions with similar lengths show very different containment times. Applying the method described in the previous section, it is also possible to follow the time evolution of the plasma radius (Fig. 4).

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